

Petrography and sedimentology of carbonate rocks in the Silurian of Gotland

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Four published papers by the author are summarized and commented upon. Two of the papers deal with localities in the Ludlovian Hemse Beds, and two deal with localities in the Wenlockian Slite Beds. The papers describe and interpret early jointing in calcarenites, preferred bipolar orientation of orthoconic nautiloids on top of calcilutite beds, wave ripple-marks and their theoretical palaeobathymetric depth of formation, and treat in detail the transition from fine-grained to very coarse-grained limestones. A comprehensive description of methods and defined constituents in petrographic modal analysis is included. Some of the inferred depositional environments are in opposition to current view.

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INTRODUCTION

This paper is the formal part of my doctoral dissertation. It summarizes and comments upon some recent results from my continuing petrographic and sedimentologic studies of carbonate rocks in the Ludlovian Hemse Beds and the Wenlockian Slite Beds of Gotland. It ends with brief accounts on some methodologic problems, the potentials of and the need for, petrographic and sedimentologic research on the Gotland Silurian succession. Finally, some perspectives are included. In addition to this compulsory summary, the thesis embraces the following papers, which will be referred to as 1 - 4 in subsequent sections.

- 1 Laufeld, S., Sundquist, B. & Sjöström, H., 1978: Megapolygonal bedrock structures in the Silurian of Gotland. Sveriges Geologiska Undersökning Ser C Nr 759. 26 pp. (9-18)
- 2 Sundquist, B., 1982a: Wackestone petrography and bipolar orientation of cephalopods as indicators of littoral sedimentation in the Ludlovian of Gotland. Geologiska Föreningens i Stockholm Förhandlingar 104, 81-90.
- 3 Sundquist, B., 1982b: Palaeobathymetric interpretation of wave ripple-marks in a Ludlovian grainstone of Gotland. Geologiska Föreningens i Stockholm Förhandlingar 104, 157-166.
- 4 Sundquist, B., 1982c: Carbonate petrography of the Wenlockian Slite Beds at Haganäs, Gotland. Sveriges Geologiska Undersökning Ser C Nr 796. 79 pp.

The island of Gotland is situated in the Baltic Sea, about 100 km east of mainland Sweden, and constitutes part of the intracratonic Palaeozoic sedimentary deposits that floor

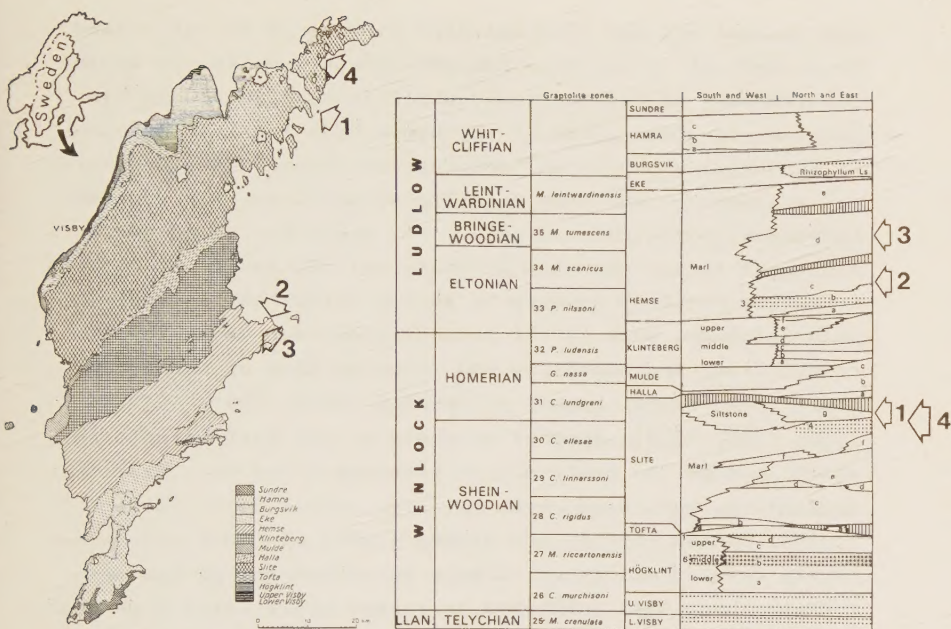


Fig. 1. Geologic map of Gotland (modified from Hede 1942) and stratigraphic scheme of the Silurian of Gotland (from Laufeld & Jeppsson 1976). The inserted figures denote geographic and stratigraphic positions of summarized papers.

much of the Baltic Basin (Martinsson 1958; Flodén 1980). The palaeogeographic position of this area during the Silurian was very close to the equator (e.g., Smith 1981). The bed-rock of Gotland is entirely Silurian in age, and made up of a variety of carbonate rocks, many with reefs, and calcareous shales ("marlstones"), claystones, and fine sandstones. These rocks originated in shallow marine and perimarine environments, which is demonstrated by the fossil fauna and flora and by sedimentary and petrographic characteristics. The data presented in paper 4 indicate deposition in the intertidal zone for parts of that sequence. Strong indications of tidal erosion and deposition have

also become evident from detailed studies of the so-called Hemse Marl SE in the Lau-Hammaren-Burgen area in the south-eastern part of Gotland (Sundquist, in prep.). Studies in progress in other parts of the Hemse Beds indicate episodes of subaerial exposure and accompanied chemical and mechanical weathering, and also possible occurrences of preserved beachrock (Sundquist, in prep.). It would not be an overstatement to say that the lithological nature of the Gotland rocks has not been studied in such a detail as has their palaeontology. Much of our present knowledge about their composition, sedimentology and inferred mode of formation comes from several papers by Hadding (1933, 1941, 1950, 1956, 1958, 1959). Special accounts on the reef structures, which through the years always have attracted most visiting geologists, have been given by, e.g., Jux (1957), Rutten (1958), Manten (1971), and Riding (1981). In addition, some papers devoted mainly or largely to sedimentology and petrography have been published in recent years (Stel & de Coo 1977; paper 1; Jaanusson 1979). A study by Watts (1981) describes in great detail the nature of the Högklint reefs and their associated sediments, but as yet no part of this work has been published.

The bedrock of Gotland was divided by Hede into 13 topostratigraphical units (Fig. 1), most of which were further divided into a number of subunits (see summaries in English 1958 and 1960; Laufeld 1974a; and Hede 1921 for a historical and bibliographical review of the stratigraphy of Gotland). The oldest strata are in the northwestern part of the island and the youngest in the south. The units are of very heterogeneous composition, thickness and extent, and are exposed as more or less parallel bands striking in a NE-SW direction and dipping generally very gently SE. Although Hede's stratigraphy still forms the framework for all geological and palaeontological activities on Gotland, and while his units are trivially used chronostratigraphically, several

detailed palaeontological and geological studies during the last decades have clearly demonstrated that most of Hede's units are in fact diachronous (e.g., Martinsson 1962, 1967; Laufeld 1974a; Laufeld & Jeppsson 1976; Larsson 1979). The degree of divergence is still far from settled and the matter is complicated because of the scarcity of continuous outcrops and the rapid lateral shifts of litho- and biofacies. For a better understanding of the origin of the Silurian bedrock of Gotland, however, the establishment of time-planes through the succession is of critical importance and a fundamental prerequisite of the reconstruction of sedimentary environments and organic communities in space and time. It has become increasingly apparent in recent years that only by the combination of a wealth of disparate investigations (palaeontological, palaeoecological, petrographical, clay mineralogical, sedimentological, geochemical, palaeomagnetic, radiometric datings etc.), would there be a reasonable possibility of finding a basis for a definition of time-planes. In view of this, a decision was made in 1979 among participants of the Swedish working group within IGCP Project Ecostratigraphy, to initiate a subproject entitled "The Whole Environment - Silurian Slite Beds, Gotland" which would focus on the time-plane problem. A brief introduction of the project was given by Laufeld (1981). Paper 4 is the first report on carried out studies in one of the three localities incorporated in the subproject. A geochemical study of the same locality by Dr. Robert E. Mosher is in preparation, and material collected from the two remaining localities is at present under study by Dr. Mosher and myself.

On the following pages papers 1 - 4 are summarized individually and briefly commented upon. Together, they demonstrate a kind of information in the Gotland succession that is made available when studied sedimentologically and petrographically. It is especially noteworthy that the con-

clusions drawn about depositional water depth in papers 2 and 4 are in conflict with the current opinion. For both of the localities treated in these papers, the present interpretation of the depositional depth of the fine-grained ("marly") limestones is "deeper water" relative to overlying coarse limestones with organic buildup structures. Therefore, to explain this lithologic shift, a regression has been invoked. My data presented in paper 2 indicate a protected littoral sedimentary environment, and my data presented in paper 4 indicate a shallow subtidal to intertidal environment throughout that sequence. In the first case it is therefore concluded that a transgression seems more likely to have occurred at the transition from Hemse Beds unit c to Hemse Beds unit d. Such an inference is supported by my studies, not yet published, of the Hemse Beds over much of their northeastern outcrop area. In the second case a minor transgression seems also likely as an explanation of the change from Slite Marl to Ryssnäs Limestone, although much of the observed lithofacies shifts in that sequence are easier to explain as reflections of variation in exposure to the open sea rather than of variation in water depth. Generally, I am of the opinion that much of the lithofacies variations in the Silurian of Gotland, both temporally and spatially, are easier to understand if interpreted as very shallow water facies mosaics, strongly influenced by tides, ephemeral incidents and normal coastal dynamical processes, with lateral variation dependence of sedimentation patterns rather than a bathymetric dependence of variations in sole control. If my conclusions and suggestions in this respect will be supported by future sedimentological and petrographical studies, as well as by other kind of evidence, they will have consequences for the general view on the development of the Gotland Silurian succession. Many of the presently inferred regressive phases will instead be interpreted as minor transgressions, and many of the presently

interpreted "deeper water" deposits show characteristics that make interpretations of shallow subtidal to intertidal depositional environments more well founded. As a matter of fact, when the Gotland geological literature is carefully searched for critical indications of depositional water depths, it is somewhat surprising to find an almost absence of such indications. Instead, expressed slightly simplified, the reasoning seems to have been that the finer the grain of the rock the deeper the water. The sedimentation of clay- and silt-sized particles is of course a much more complex mechanism than solely dependent on water turbulence, or above or below wave-base. Biological activities, salinity changes, organic matter in the water etc. have been shown in a number of publications to have fundamental influence on the deposition of terrigenous fine material. The origin and sedimentation of the carbonate fine particles is possibly even more complicated, but certainly there is no simple rule stating that its deposition is in deeper water. Because much of the carbonate "mud" might be derived from the disintegration of green algae, a shallow water deposition seems more plausible.

MEGAPOLYGONAL BEDROCK STRUCTURES

Paper 1 describes and interprets an occurrence of a megapolygonal bedrock structure in a calcarenitic limestone in the Slite Beds unit g. The structure consists of 0.5 - 1.2 m wide and 0.3 - 1.0 m high polygonal ridges, 5 - 15 m across, and was found on Bungeör, a small islet between Fårö and mainland Gotland. The megapolygons have a central crestal fissure, and these fissures are surface expressions of polygonal master joints. A study of thin sections from the ridges and from the "basins" inside the polygons shows that the particles of sand size is about identical as to kind

and amount, while the amount of micrite is of major difference. The limestone at the ridges contains about six times as much micrite as that inside the polygons. The rocks are made up primarily of skeletal debris, mainly echinoderms, and (in smaller amounts) of bryozoans, brachiopods and arthropods, and of micrite and sparry cement. Most of the bioclastic debris is well rounded and of sand size, but the sorting is poor. The texture of all samples is grain-supported, and because the rocks contain some mud, they are all packstones. A striking feature of the samples from the "basins" is their high original porosity as compared to the ridge samples. All the pores, being fenestral and vug, are completely filled by sparry calcite. The amount of insoluble residue in the samples is very small but still is ten times as much in the ridge samples than in the "basin" samples. The residue consists of pyrite, limonite, clay, and dolomite rhombs. Of prime interest is the great difference in the amount of micrite between the ridge samples (c. 25%) and the "basin" samples (c. 4%). Because the rocks are postulated to be synchronous, the micrite variation cannot be primary. It is therefore evident that either all rocks originally had a high content of micrite, or that the micrite in the ridge samples is secondary in origin. Because of fabric criteria it is concluded that the first possibility is unlikely, and because of the presence in all samples of a first generation cement, the inference seems justified that the micrite mainly is secondary in origin in the ridge samples. In the "basin" samples, the pore space that remained after the first thin scalenohedral calcite crystals lining, is filled by large crystals of clear calcite, which then constitute the second and final cementation. In the ridge samples, on the other hand, the pore space left after the initial cementation is filled by micrite. Hence, micrite is not only present in larger quantities in the ridge samples but is concentrated in the pores, separated from the primary

sedimentary particles by the first generation cement. The micrite therefore postdates this cement. In conclusion it is evident that the original sediment was a skeletal sand with the depositional texture of a grainstone and that the micrite was introduced into the sediment via the joints after the first generation cement but before the final pore-filling cementation. Therefore, it is also concluded that the jointing must have occurred at a relatively early stage during diagenesis. The mechanism inferred is that mud-rich water, coming probably from below and under some pressure, could penetrate the semi-lithified skeletal sand when the fissures opened, and because of the porous structure the muddy water also entered into the sides. The micrite was thus filtered off during the lateral passage of the first 0.25 - 0.6 m at both sides and this "injection" transformed the texture to that of packstone. The polygonal structure that can now be seen is due to present day differential erosion in which the micrite-rich limestone has a better resistance because of a higher density. An analysis of the joint directions suggests a local cause of the polygonal jointing, and a centrifuge model experiment indicates that polygonal joint patterns can be formed on top of buried reefs. Two general conclusions are drawn in this paper, viz., that mapping of structures of this kind might become an important tool in palaeogeographic reconstruction of reef areas, and that joint related rocks exhibiting the same microstructural characteristics as those demonstrated herein might well explain the formation of sea stacks, raukar, on Gotland.

Comment. - Preliminary results from other localities on Gotland with similar polygonal joint and ridge structures show similar microstructural textures with regard to presence and position of micrite in the rock. These studies are not yet finished. Soon after the publication of this paper I received an interesting response. In a letter dated

25 Sept. 1978, Dr. Robert N. Ginsburg writes "Reading your descriptions and looking at the photographs made me think of the jointing in beachrock", although he says he has never seen it on the same scale. In the paper I noted some occurrences of pendent first generation cement, but under the circumstances thought it to be unlikely that the jointed bedrock on Bungeör could be a beach deposit, because it was generally agreed on that these rocks had accumulated at some depth. In view of the inferred depositional water depth for the lower part of the same stratigraphic unit at the locality Haganäs 1 (paper 4), however, a beach deposition now cannot be excluded. To verify this, the locality has to be revisited and bedding studied in detail, and further sampling undertaken. The jointing in beachrock originates from thermal contraction and expansion which, in such a case, make differential compaction over buried reefs unnecessary in explanation of the polygonal jointing. Dr. Eugene Shinn points out to me in a note from 1978, the apparent similarities between the polygonal structures on Bungeör and polygonal fracture patterns found in Holocene carbonate sediments in the Persian Gulf. He refers to Shinn (1969), but the polygons described in that paper are anticlinal in cross-section and are due to lateral expansion caused by submarine cementation. Because the bedding at Bungeör is planar a mechanism of this kind cannot explain the origin of the structures there.

WACKESTONES AND BIPOLAR ORIENTATION OF CEPHALOPODS

Paper 2 describes and interprets an occurrence of wackestone beds, each of which is terminated by a layer of orthoconic nautiloids showing preferred orientation, and a thin bed of calcareous shale. In the NW part of the locality Grogarnshuvud 1 (Laufeld 1974b) there is a composite bedset of inter-

layered fine-grained limestones and calcareous shales. The beds dip a few degrees to the E and have been eroded so that four bedding planes are exposed. The limestone beds have a thickness of 7-13 cm and the shaly beds a thickness of about 1 cm. This exposure constitutes the basal part of Hemse Beds unit c. The four bedding planes contain orthoconic nautiloids in abundance, and also gastropods and the pelecypod Ilionia prisca (usually found in vertical inferred life position). The directions of the apical end of 321 individual nautiloids were recorded, the axes of which are parallel to the bedding planes. The length of the shells, many of which are broken along a septum, varies between c. 10 and 60 cm and the majority are c. 15-20 cm. The apex orientations of the nautiloids show a distinct bipolar pattern on every bedding plane, and it is concluded that the most likely explanation is orientation due to wave action. On three of the bedding planes, the orientation pattern is not two completely opposing maxima, but form an obtuse angle which indicate a wave progression from ESE. The four bedding planes that contain the orthocones are very irregular but the beds are laterally persistent. The rocks are greyish brown and have a fine-grained mottled texture completely devoid of lamination. Shell debris is randomly oriented and sparse. The thin shaly partings are grey to greenish grey and finely laminated. A thin section study of the limestone beds show great similarities between beds, and that the main constituent in all beds is microspar (c. 60%), that pellets make up c. 13%, micrite c. 8%, and skeletal grains c. 10-20%. Because the similarities between the beds are far more conspicuous than the differences, it is assumed that the sediments were deposited under fairly constant conditions. The origin of the microspar is inferred to be neomorphic because of fabric criteria and the mud-supported texture. It is therefore concluded that the microspar originally was a calcareous mud, and hence the depositional texture of these rocks was that of wackestone. The

inference is made that the nautiloids were stranded, which is based on the following observations: 1) the large number of shells in a relatively small area indicates a thanatocoenotic concentration which is most easily explained by stranding and reworking by waves, 2) no nautiloid shell is found vertically embedded but instead all have their long axis parallel to bedding, 3) the repeated presence of nautiloid shells only on bedding planes and never within beds is critical, because a more random occurrence would be expected if the shells had sunk through a water body more or less continuously. The inferred original composition of the limestone beds is a pelletiferous calcareous mud with scattered skeletal fragments representing a marine biota of low diversity. This mud was certainly inhabited by the pelecypod Ilionia prisca and also probably by gastropods and dasycladacean algae. Using the Holocene as an analogue the depositional environment of these rocks is interpreted to be marginal lagoonal. The series of events that would result in the actual kind of bedding at Grogarnshuvud 1 is concluded to have been the following: 1) the calcilutite beds represent the normal situation of slow deposition at the margin of a protected lagoon, 2) the nautiloid shell accumulations represent ephemeral incidents, such as a storm, which brought together a large number of floating shells into the lagoon where they were stranded and became oriented parallel to shore due to intense storm-wave action, 3) the calcareous shale beds represent the final stage of the incidents with the settling of agitated suspension load. In consequence, this interpretation implies that the current opinion that the buildup phases during Hemse time (subunit d) were initiated during one or several regressions is incorrect. The development which would be in accordance with the results from this study is instead one or several transgressions.

Comment. - After the submission of the MS of this paper

I have come across some additional references with regard to the post-mortem orientation of shells, viz., Kelling & Williams (1967), Brenchley & Newall (1970), Loubere (1977), and Gnoli et al. (1979). The first three are mainly based on observations from flume experiments and deal with uni-directional currents, while Gnoli et al. confirm interpretations from geological observations by flume studies of orthocone cephalopods. None of these papers add significant information for my conclusions to be revised.

PALAEOBATHYMETRY AND WAVE RIPPLE-MARKS

Paper 3 describes and interprets a ripple-marked grainstone bed in terms of wave conditions and absolute water depth. The ripple-marks occur in the SE part of the quarry-floor at the locality Gannes 3 (Laufeld 1974b). Quarrying has cut into a sequence of stratified sparitic calcarenites and calcirudites, and some minor buildups. The entire exposure within the quarry belongs to the lower part of the Hemse Beds unit d. Most of the limestone beds have a thickness of c. 6-10 cm, being light yellowish grey to light brownish grey and separated by thin clay partings which in places pass into stylolites. The bedding is wavy to even and mostly parallel. The rippled bed is about 25 cm thick and is exposed over an area of about 100 m². The lower surface of the bed is heavily stylolitized, and in the quarry wall the bed is overlain by a clay layer which is about 1 cm thick. A study of etched slices and thin sections yield the following information: 1) There is no obvious primary internal lamination. Stylolites are present but because of their insignificant amplitude and obvious parallelism with the surface it is inferred that the solution compaction has not changed the bed configuration. 2) No distinguishable difference with regard to average grain size exists between

the samples. The bed is composed of skeletal debris and cemented with clear calcite spar, and the depositional texture of the sediment was that of grainstone. 3) Grain size ranges from coarse silt to fine gravel, with 99% in the sand fraction, and the mean size is 0.52 mm (coarse sand) and sorting is moderate. The most prominent feature of the bed surface is the ripple train, but this is superposed and deformed by burrowing and crawling organisms to the extent that the entire surface is covered by traces. Almost all ripple crests are flat and some are concave. According to the literature, such deformation structures can be ascribed to a change in flow regime in connection with falling sea level and the accompanied scour of the crests, caused by e.g. the withdrawal of the tide from a beach. A mechanism of this type seems reasonable as an explanation of the flat and concave ripple crests at Gannes 3. A penecontemporaneous erosion (or scouring) of the ripple crests is also indicated by the presence of traces on the surface. These were evidently formed after the flattening of the ripples, and their good preservation means that no sediment transport nor any erosion took place subsequently. The clay layer which originally covered the surface (verified in the quarry wall) is therefore inferred to have been deposited rapidly and might be ascribed to slack-water or a period of strongly decreased water motion. Although the ripples are deformed, both internally and externally, several lines of evidence strongly indicate a wave origin of the ripple-marks. My interpretation of the ripples in terms of ancient wave conditions and absolute water depth is based on several studies published during the last decade and primarily the studies by Komar (1974) and Allen (1979). The three parameters that must be known for the interpretation are grain size, ripple spacing, and the vertical form index. With regard to the ripples at Gannes 3 these are 0.52 mm, 63 cm, and 5.5, respectively (the vertical form index had to be calculated from a reconstruction assuming

a trochoidal trough shape which characterizes vortex ripples). The ripple existence-field for the train is estimated to vary in wave period (T) between 3.8 and 33.5 s, and in water-particle orbital diameter (d_o) between 0.63 and 1.92 m. Knowing the extreme combinations of T and d_o , and with the reasonable (and necessary) assumption that the near-bottom water-particle orbital velocity originated at the water surface, it is feasible to calculate the wave conditions required to produce the necessary near-bottom orbital velocity. By using a series of equations from Komar (1974) the deep-water wave length, the wave length, and the wave height could be calculated for various water-depths. The resultant values were plotted graphically and tested for wave stability. By adding along the abscissa and the ordinate in the graph, the conditions of maximal normal, storm, and maximum figures recorded (with reference to present day wind generated waves), the range of plausible combinations within the existence-field is strongly limited. It is concluded that by applying a d_o value in agreement with empirical coefficients, and considering the general wave climate, the ripple-marks at Gannes 3 might have been generated by waves with a period of about 11 s and a d_o of about 0.9 m, at a water depth of 10 m or less. In view of the lithofacies setting such a depth figure seems quite reasonable.

Comment. - I clearly realise that many of the inferences and assumptions that are made in the paper in order to make an interpretation possible, might well be subject to discussion. One such critical point is the effective grain density. Nothing is virtually known about the sediment accumulation rates in the Silurian Gotland sea, but if present day intragranular crystal growth rates in carbonate supersaturated shallow seas are applicable here, a time period of up to some thousand years would probably be required for a 80-90% fill, as inferred. If no such cementation occurred

or occurred in a significantly smaller quantity, the calculations have to be revised because not only is the particle density decreased but also one has to deal with particles that are porous. Another critical point is the mean grain size, the reliability of which is particularly difficult to judge when dealing with biogenic skeletal debris. After submitting the MS of this paper I am aware of the publication of two articles of direct interest for the evaluation of wave conditions and water depth in ancient ripple-marks. P.A. Allen (1981) emphasizes some critical aspects of ripple form and points out possible pitfalls, and Moore (1982) makes comparisons of various models for the interpretation of water depth and fetch, with regard to fine-grained epeiric-sea deposits.

METHODS, ANALYSES, AND MEANS OF INTERPRETATION

Paper 4 describes and interprets a sequence of 2.73 m, covering the transition from micritic and microsparitic carbonate rocks with intercalations of calcareous shales and silty claystones (Slite Marl), to coarse- and very coarse-grained limestones with intercalations of calcareous shales and microsparitic carbonates (Ryssnäs Limestone). The paper also contains a comprehensive description of study methods, and various techniques of analysis. The significance of constituents and sedimentary structures for the interpretation of depositional environments is also briefly discussed. The locality Haganäs 1 (Laufeld 1974b) is the southeastermost portion of a c. 3.5 m high beach cliff, exposed for a distance of about 250 m. The section was sampled from just above sea level upwards until the lithologic transition was considered sufficiently covered. A total of 56 samples were collected, most of which represent a stratum and a few represent a part of a stratum in the section. The average

sample size was about 15 cm in length, 10 cm in width, and 5 cm in thickness. Approximately 3-4 slices, each about 10 mm thick, were cut in series from each sample perpendicular to bedding. A grinding and etching procedure yielded a set of sample slices in which all essential properties with respect to average grain-fabric and internal structures were easily examined. A total of 100 thin sections, representing 86 stratigraphic levels in the section, were modally analysed by means of point-counting. The grand total of points incorporated in the analysis amounts to 62,069. Specially designed recording forms were used in the modal analysis and these forms list 38 alternative constituents, empirically known to occur, and for some of these also indication of relative position. In total the recording forms distinguish between 81 variables, 50 of which deal with clastic biogenic constituents, 9 deal with clastic biogenic or abiogenic constituents, 6 with clastic abiogenic, 6 with clastic abiogenic or authigenic, and 9 deal with authigenic constituents. The 81st variable indicate presence of micrite envelopes. The modal analysis data are presented in a diagram together with significant sedimentary structures, and are also plotted in time-trend analyses. The section is lithologically described bed by bed in great detail. The normalized raw data from the modal analysis were also run in a computer for a principal components analysis (PCA), and it is concluded that the PCA gave no new information critically needed for interpretation of the data, but seem to indicate that a four-part division of the sequence is justified with regard to the overall average grain-size characteristics. A lithostratigraphic subdivision of the section is made, and subdivisions described and characterized in terms of particle composition, sedimentary structures, and bedding characters. The Slite Marl at this locality is divided into three lithozones, and the Ryssnäs Limestone shows characters quite distinct from the Marl. The environments of

deposition of these rocks are considered and comparisons with Holocene environmental characteristics are made. Also some general reflections are communicated with regard to depositional interpretations. With regard to sedimentary structures and associated characteristics, it is concluded that there are indications for shallow subtidal to intertidal depositional environments throughout the sequence. The lower and upper part of the Slite Marl are here of more intertidal character while the middle part of the Marl and the Ryssnäs Limestone are of more subtidal character. With regard to constituents it is not so simple to infer a definite origin for them in terms of depositional site. The problems that arise and their possible solutions are considered briefly. The statement is made, however, that it seems possible to conclude that the Slite Marl in general, and for a majority of included beds in particular, has both an average lower number of skeletal biogenic constituents and an average lower biogenic diversity as compared to the Ryssnäs Limestone. Therefore it is also concluded that the kinds and amounts of biogenic debris present do not contradict a shallow subtidal to intertidal depositional environment. In explanation of the lithologic changes in the section, some of which are sharp and erosive, it is suggested that these could be interpreted as reflections of variation in exposure to the open sea rather than of variation in water depth. In such a model the observed changes could be ascribed to effects of storms on coastal morphology in the construction and destruction of shelf barriers. Therefore, the Slite Marl is mainly indicative of a protected depositional environment, and the Ryssnäs Limestone indicative of a mainly exposed depositional environment. The conclusions drawn from this study with regard to geologic development and depositional environments are not in agreement with the current opinion which infers a regressive phase as an explanation of the transition from fine-grained Slite

Marl to Ryssnäs Limestone.

Comment. - The MS of this paper was submitted just recently and much of my thinking is expressed in the paper.

PROBLEMS, POTENTIALS, AND PERSPECTIVES

Many of the problems involved in environmental reconstructions based on petrographic modal analysis are discussed in paper 4. Methods for solving these problems are presently under study and consideration, and I think that future results from detailed palaeontologic studies within the subproject "The Whole Environment" will be of ultimate importance for the evaluation of quantitative data from petrographic analyses of these rocks. Also, I think that these results will have great impact on future petrographic and sedimentologic research on Gotland, and that it will be possible to make generalizations applicable to much of the Silurian succession on Gotland.

Sedimentologic descriptions of rock sequences are almost lacking from Gotland. With future studies of this kind at key localities, I am convinced that interesting and revolutionary information will appear, which in turn will make interpretations of depositional water depths and sedimentologic environments and mechanisms firmly based. With more accurate knowledge of these I am certain that general trends can be detected and applied extensively on Gotland.

One branch of sedimentary petrographic research that would add tremendously to the present knowledge is cementation studies and the establishment of cement stratigraphy. With the aid of cathodoluminescence equipment such studies have advanced impressively in recent years (see, e.g., Longman 1980; Flügel 1982). Such studies have shown to be a "golden key" to many intricate problems that have faced geologists for years. The detailed cementation history of

a rock can be traced accurately and the development in cementation stages may provide an additional basis for stratigraphy and the establishment of time-planes in complex geological situations.

To end this paper I would like to refer to Gretener (1967) who refers to Barth who refers to Arthur Conan Doyle who has Sherlock Holmes to actually say "It is an old maxim of mine that when you have excluded the impossible, whatever remains, however improbable, must be the truth".

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